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Demonstrating the Persistence and Heavy Payload-Carrying Capability of the Liberdade Flying Wing Glider

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LONG-TERM GOALS

The long-term goal of this program is to develop a new class of underwater glider (the Liberdade class) optimized for long distance, long duration (persistent) flights in the ocean. Central to this objective is increasing the horizontal transport efficiency, speed, and payload capacity of underwater gliders. The approach used in this program is to exploit the high lift-to-drag ("finesse") properties of the flying wing design. A parallel, and equally important, goal is improving the sensing capabilities and automated decision-making capability based on the outputs of onboard sensor systems. In addition to acting as a persistent, mobile, sensing node in a future system, and providing a persistent, high-spatial-resolution, real-time monitoring capability for the presence of marine mammals, this new glider provides a novel capability for data collection in support of basic ocean science.

OBJECTIVES

The primary technical objective this past year was to test and evaluate the at-sea performance of the new flying wing underwater glider, "Liberdade/ZRay". Innovations incorporated into this new glider include a) movable, camber-changing, trailing-edge flaps in order to achieve nearly double the lift-to-drag ratio of the Liberdade/XRay glider, b) small water jets in the wing to provide thrust at neutral buoyancy for fine control over both the horizontal and vertical orientations of the wing, c) a novel pitch mass system conformal to the glider's outer shape in order to save internal space, and d) space for four large sensors (e.g., low frequency acoustic vector sensors and/or very wide bandwidth hydrophone packages), one in each wingtip, one in the tail along the centerline, and one in the nose cone to supplement the 27-element hydrophone array in the sonar dome all along the leading edge of the wing. A second technical objective was to further advance the glider's onboard real-time signal processing capability to provide real-time marine mammal monitoring and mission adaptability, as part of ZRay's participation in ONR's Glider-Based Marine Mammal Monitoring program. These objectives build upon the experience gained in 2006-2008, the first three years of at-sea deployments with XRay, our first fully autonomous flying wing underwater glider.

APPROACH

The Liberdade flying wing underwater glider program is a team effort between the Marine Physical Laboratory, Scripps Institution of Oceanography (MPL/SIO) and the Applied Physics Laboratory, University of Washington (APL/UW). The purpose of this partnership is to combine the specialized expertise that exists at our two institutions in the areas of autonomous vehicle technology and automated passive detection, classification, and localization in order to develop robust, high performance gliders based on the flying wing design that can perform useful missions. This partnership has been essential to the success of the program.

The original concept of an underwater glider based on the flying wing design was proposed in the 2003 Glider System Study sponsored by ONR (Jenkins, Humphreys, Sherman, et al., 2003). The purpose of this study was to evaluate the present state of development in underwater glider technology, examine the various roles for autonomous underwater gliders in Navy missions, and identify additional developments in glider technology required to realize the potential of underwater gliders. The flying wing design was recommended for those missions requiring optimal horizontal transport efficiency. Horizontal transport efficiency, or specific energy consumption, is defined as the energy consumed per unit distance traveled for each unit of net vehicle weight. For an underwater glider that travels along a glide angle, γ, with respect to the horizontal, the power consumed P_e to overcome drag F_D is equal to the rate of working by gravity along the glide slope, $\tan\gamma = w/u$:

$$P_e = \vec{F}_D \bullet \vec{U} = \left(\vec{F}_b - \vec{F}_g\right) \bullet \vec{U} \Rightarrow F_D U = \left(F_b - F_g\right) w \qquad (1)$$

The quantity $\vec{F}_b$ is the buoyancy force (F_b is its modulus), $\vec{F}_g$ is the weight of the glider in air, u is the horizontal component of the glide velocity (*cross country speed*), w is the vertical component of the glide velocity (*sink rate*), and $U = \sqrt{u^2 + w^2}$ is the *glide speed*.

In applying concepts of horizontal transport economy to underwater gliders, the immersed weight (or net buoyancy, $F_b - F_g$) represents the net weight transported over half a dive cycle by the action of energy consumption. If an underwater glider has no immersed weight, no motion other than passive drifting occurs and no energy of forward propulsion is consumed. Energy is consumed in an underwater glider by the buoyancy engine that generates a variable displaced volume increment $\pm V_b$, allowing net buoyancy to alternately be changed between positive and negative states, $F_b - F_g = \pm\rho g V_b$, where ρ is the seawater density. The buoyancy engine gives the underwater glider the ability to propel itself forward in a series of descending and ascending glides. Only the horizontal component of the glide speed, *u*, results in horizontal distance traveled point-to-point. Consequently, the specific energy consumption (net horizontal transport economy) of a glider is:

$$E_e = \frac{P_e}{u(F_b - F_g)} = \frac{w}{u} = \tan\gamma = \left(L / D\right)^{-1} \quad (2)$$

The glide slope, $\tan\gamma$, is equivalent to the reciprocal of the lift-to-drag ratio, $\left(L / D\right)^{-1}$, and provides a quantitative measure of horizontal point-to-point transport efficiency. The lift-to-drag ratio of a wing also is called its "finesse". A small glide slope (large *L/D* and large finesse) allows an underwater glider to travel a given horizontal distance in the fewest numbers of buoyancy engine cycles and therefore consume the least amount of energy in forward propulsion.

Other existing underwater gliders - Seaglider, Spray, and Slocum - are designed primarily to collect vertical profiles of water column properties and move only short distances at low horizontal speed from one profile to the next. A large lift-to-drag ratio is not a design criterion for these gliders; rather, they are well suited for their "vertically profiling" task. As such, they have revolutionized the field of oceanography. By maximizing horizontal transport efficiency, the role of the Liberdade class of underwater glider is synergistic and complementary with the role of these other gliders.

Bigger gliders are more efficient at horizontal transport. Surveys of natural and man-made flyers (McMasters, 1974) confirm this relation across 12 orders of magnitude range in size. In addition, the square-cubed law from classical aerodynamics indicates that larger flyers also achieve higher cruise speeds with greater payload capacity, two additional performance objectives in this program. This size advantage is accentuated in underwater gliders due to economies of scale in packing efficiency. All these factors suggest that to achieve the performance goals in this program, the largest glider that can be deployed from the available launch and recovery platform should be designed and built. Therefore, the Liberdade/Stingray, Liberdade/XRay, and Liberdade/ZRay gliders are scaled up to the largest size that can be easily accommodated on the work deck of R/V Sproul, the smallest of the UNOLS ships operated by the Scripps Institution of Oceanography. The resulting flying wing gliders have 20-ft wing spans and total internal volume in the 1,000 liter range.

In addition to size, other design factors are important to consider in reducing energy consumption in horizontal transport. Of all the outer shape properties of the glider influencing the specific energy consumption, the one with the strongest influence is the wetted-surface-to-wing-area ratio so that reducing this ratio will achieve the greatest improvements in horizontal transport economy. The smallest ratios are associated with flying wing and blended wing body geometries (such as used by birds) yielding ratios in the 2.2 to 2.4 range. The other benefit of a large wing area is that it reduces the coefficient of lift and the associated induced drag (the largest component of drag at minimum specific energy consumption). However, increases in wing area must be balanced with increasing the wing aspect ratio, which exerts a greater reduction in specific energy consumption than does a proportionally smaller lift coefficient. Increases in aspect ratio, in turn, must be balanced with the structural limitations of high aspect wings, especially when flooded with seawater.

In order to capitalize on these findings and the results from the at-sea tests of Stingray in 2004, a team of scientists, engineers, and technicians was formed between the Marine Physical Laboratory, Scripps Institution of Oceanography (MPL/SIO) and the Applied Physics Lab, University of Washington (APL/UW). The major portion of the engineering team at MPL/SIO is comprised of members of MPL's Ocean Vehicle Development Group. This group has a long history of developing advanced remotely operated vehicles for deep ocean research and exploration. It also is responsible for improving, maintaining, and operating MPL/SIO's set of prop-driven AUVs. MPL/SIO also contributed personnel who participated in the ONR Glider System Study and led the design and at-sea testing of Liberdade/Stingray. The group at APL/UW has been instrumental in developing the highly successful Seaglider program. In addition, this group has a great deal of experience in underwater acoustic communications, Navy advanced system development, automated detection, classification, and localization (DCL) algorithm implementation for operational sonar systems, and in flight control and flight simulation software for advanced aircraft. The work accomplished by this team of scientists, engineers, and technicians over the past year is summarized in the following section.

WORK COMPLETED

The first quarter of FY11 was spent preparing for the Range Validation Test on the Navy's SOAR Range, the instrumented part of the SCORE Range. Activities included preparing and submitting the environmental paperwork for the exercise, preparing a test plan, and coordinating the participation of seven different research groups from six different institutions (the Marine Physical Lab/Scripps Institution of Oceanography, the Applied Physic Lab/University of Washington, Woods Hole Oceanographic Institution, National Oceanographic and Atmospheric Administration/ Oregon State University, Naval Undersea Warfare Center Newport, and SPAWAR Systems Center Pacific). Due to additions of Navy exercises to the SCORE Range schedule in the last half of 2010, the Range Validation Test had to be delayed numerous times. The test finally was conducted the first week of January, 2011, during the Range's official holiday closure period.

The Range Validation Test represented the first at-sea deployment of ZRay. Therefore, preparations for the test also included ballasting, trimming, and testing the glider's subsystems, and writing, testing, and debugging its modified set of flight software and real-time signal/array processing software. The real-time algorithm performs detection, classification (partially), and localization (DCL) tasks and operates on the outputs of ZRay's 27-element hydrophone array. This array is located inside a sonar dome all along the wing's leading edge. It has 15 kHz per channel bandwidth, although it was configured for only 10 kHz per channel bandwidth during the Range Validation Test. It permits high-spatial-resolution localization of low and mid-frequency sounds including mysticete vocalizations and man-made sounds such as surface ships and active sonar. The outputs from this array are connected to a small, low-power, single-board computer inside the glider's payload housing, which runs the real-time DCL algorithm string. This DCL string was designed initially for humpback whale calls, but now is being generalized for a wide range of marine mammal species.

In addition to the leading-edge hydrophone array system, ZRay also was equipped with two additional passive acoustic monitoring systems, 1) a very-wide-band (10 Hz to 100 kHz), single-hydrophone mini-HARP system from MPL/SIO and 2) a three-channel (two mid-frequency channels and one low-frequency channel) Digital Monitoring (DMON) system developed at the Woods Hole Oceanographic Institution. Both the mini-HARP and DMON systems were configured in record-only mode. The CAD/CAM drawing of ZRay in Fig. 1 shows the locations of these passive acoustic sensor systems in the glider.

ZRay's upper starboard-side hatch cover in Fig. 1 has been removed to expose various subsystems including one of the buoyancy engine tanks (purple cylinder with silver endcaps), two 3.3 KW-hr lithium polymer batteries (pink boxes), a data acquisition electronics pressure housing (gray sphere), and the fluid-based roll control system's starboard reservoir (upright teal cylinder with pink endcap). Because ZRay is designed to be inherently stable in flight, the need for activating its flight control systems while on descent or ascent is minimized, thereby eliminating self noise contamination on the onboard passive acoustic sensors. Results from the Range Validation At-sea tests clearly illustrate the inherent flight stability of this new glider, as discussed in the next section.

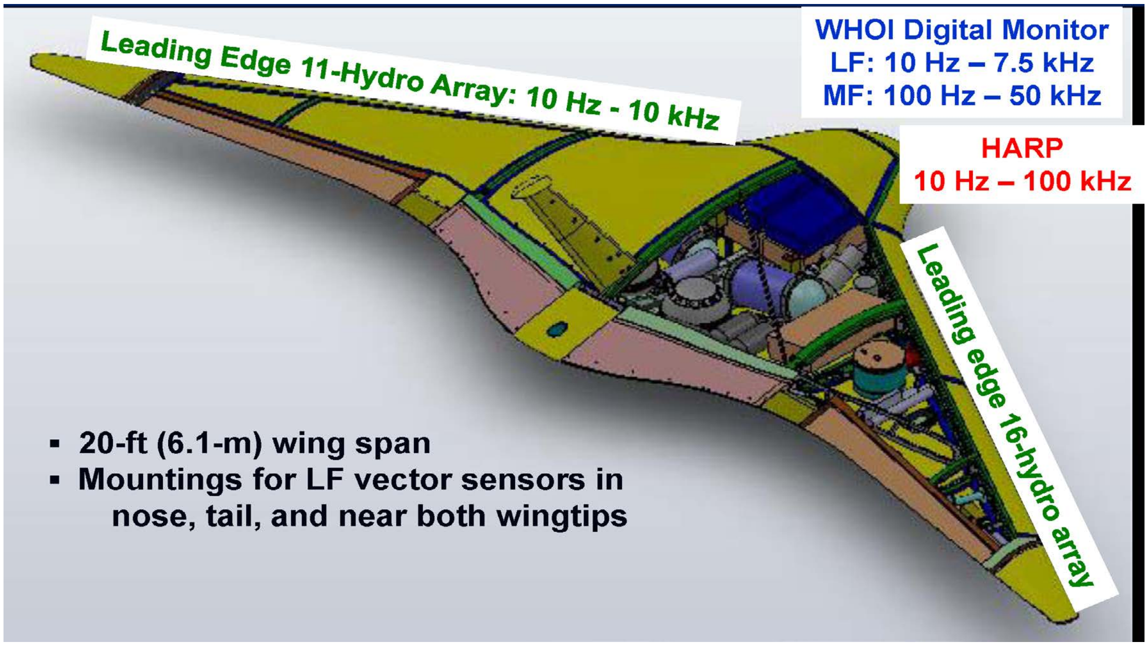

Figure 1. CAD/CAM drawing of ZRay with the starboard hatch covers removed and with labels illustrating the locations of the glider's real-time passive acoustic monitoring systems.

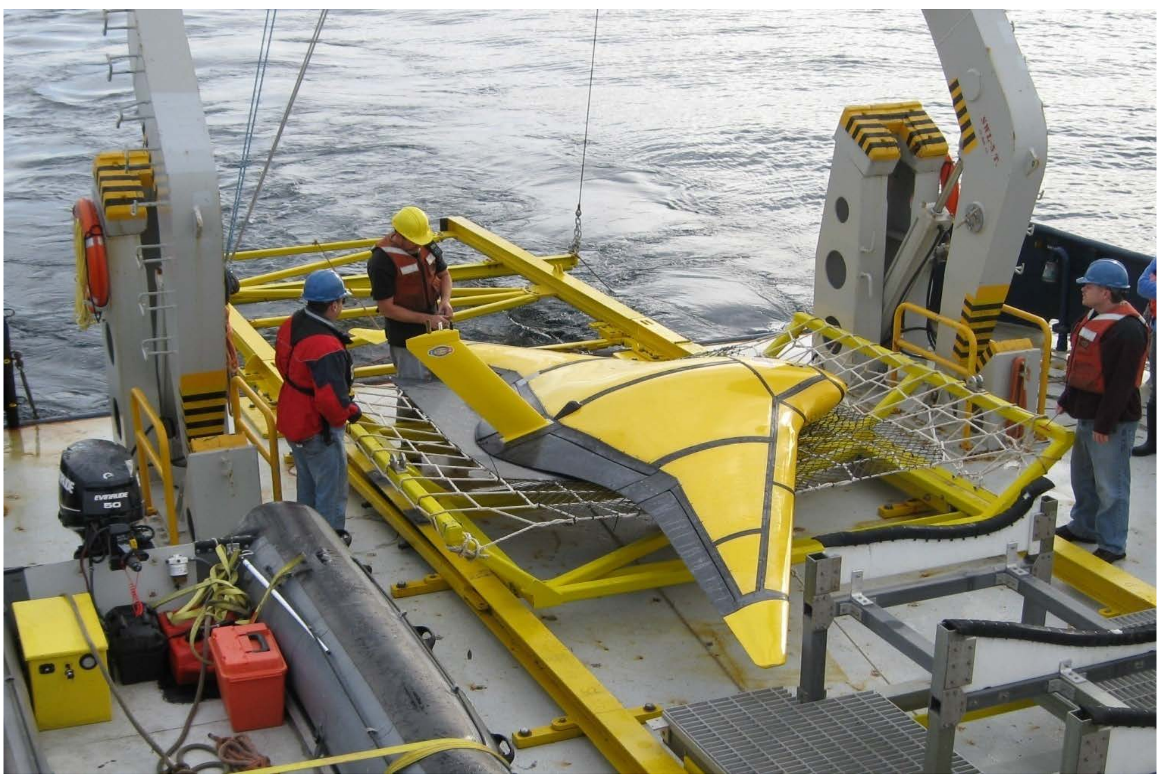

Figure 2. Photograph of ZRay resting on its deployment cart on the fantail of the R/V Sproul during the Range Validation Test, January, 2011.

A photograph of the ZRay glider on the fantail of R/V Sproul during the Range Validation Test is shown in Fig. 2. The outer shroud is made of ABS plastic and is mounted to a titanium inner strength structure. All subsystems required for the glider's fully autonomous flight also are mounted to this internal strength structure. These subsystems performed nearly flawlessly during the glider's 25 missions in the Range Validation Test.

The Range Validation Test was highly successful in almost all aspects for all participating organizations. Figure 3 identifies the set of autonomous platforms and passive acoustic data collection systems employed during the test in addition to the ZRay flying wing glider. The autonomous underwater vehicles included two single-hydrophone-equipped Seagliders able to dive to 1000 m in order to detect beaked whales (upper left), and a Slocum glider from Woods Hole equipped with a DMON system (lower left). Two autonomous surface vehicles called Wavegliders made by Liquid Robotics, Inc were deployed, each equipped with a single towed hydrophone system (middle right). One Waveglider was operated by the MPL/SIO and the other by SPAWAR SSC Pacific. Three freely-drifting autonomous buoys (lower right), each equipped with a single hydrophone system, also were deployed, one from NOAA/Oregon State and two from Woods Hole. All autonomous platforms were deployed over the field of bottom-mounted range hydrophones comprising the Navy's SOAR Range (outlined in yellow in the map in the upper right of Fig. 3). The NUWC Newport detector outputs from all SOAR Range sensors were recorded over the test duration by NUWC Newport personnel.

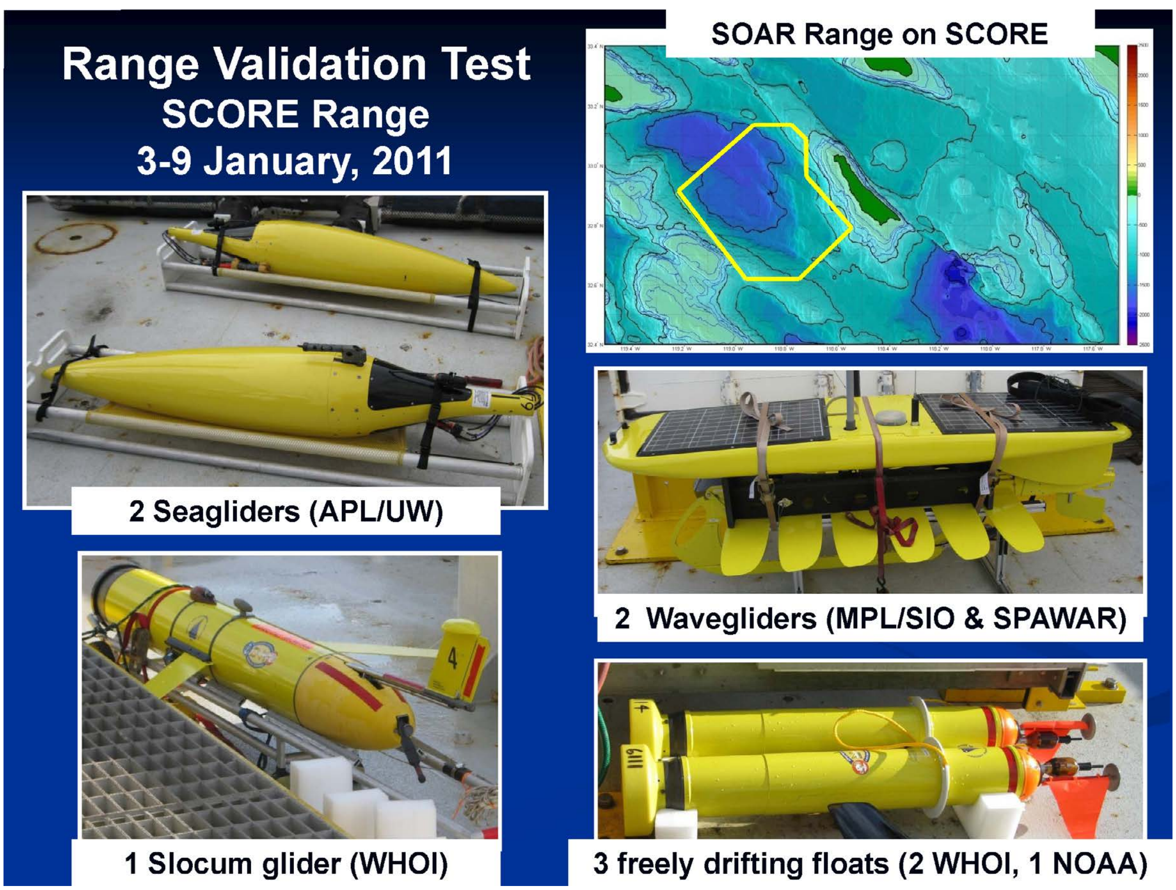

Figure 3. Photographs of the autonomous platforms and passive acoustic recording systems deployed during the Range Validation Test in addition to the ZRay flying wing autonomous underwater glider shown in Fig. 2.

All data recorded by the various passive acoustic data acquisition systems have been fully processed by the institution responsible for collecting the data. Results from the processing were presented at the ONR Passive Acoustic Monitoring of Marine Mammals program review 6 April, 2011. Subsequently, the results from the real-time detection/localization algorithm operating on ZRay's leading-edge array outputs were used to adjust the algorithm string and its input parameters to improve performance. As part of this effort, a near-optimal algorithm for detecting transient signals was developed, tested, and implemented at no cost to the flying wing glider program. The development of optimal detectors begins with the Likelihood Ratio Test (LRT). Application of the LRT, with approximations, leads to a power-law detector with a power significantly greater than that of an energy-based detector in the case of narrow-band transient signals. A peer-reviewed paper has been accepted for publication describing the development of a modified power-law detector for transient signals (Helble et al., 2011).

After the Range Validation Test, some minor modifications were made to ZRay. The most significant change was to install a third actuator to control the trailing-edge flaps. Follow-on sea trials to test these modifications, as well to fully characterize the acoustic performance of the flying wing glider's passive sensor systems and real-time algorithms and to further exercise the Iridium satellite link to monitor and control the glider's missions remotely, are scheduled for October and November, 2011.

RESULTS

During the Range Validation Test, the new ZRay glider demonstrated inherently stable flight, thereby significantly reducing onboard power consumption required to control flight. Another important result of inherently stable flight is that the acoustic and vibration self noise recorded by the onboard passive acoustic monitoring systems also is significantly reduced. One result from ZRay's deployment during the sea test is shown in Fig. 4. The red curve is the ratio of the horizontal to vertical components of velocity of the glider through the water. These data were collected by the glider's very high frequency angle-of-attack sensor during a dive on the first day of testing. This ratio of the components of velocity approximates the Lift-to-Drag (L/D) ratio, or "finesse" of the glider.

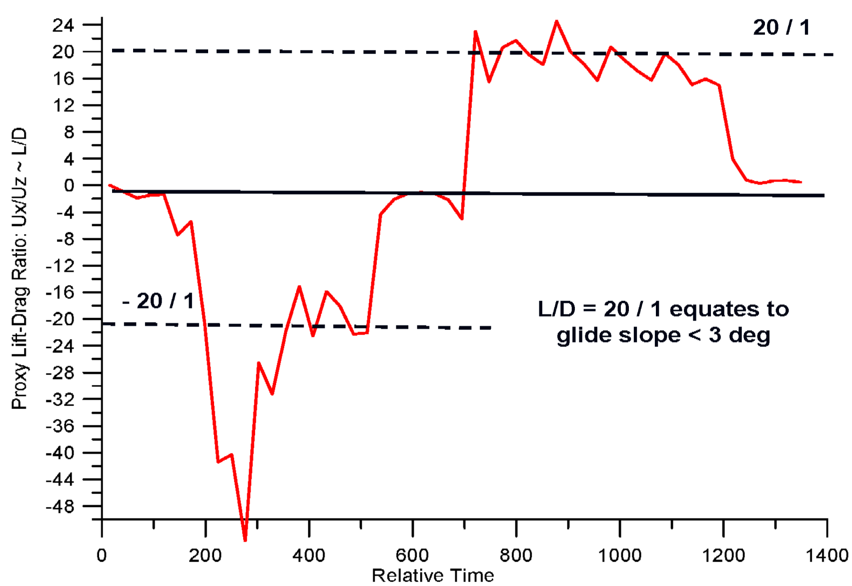

Figure 4. Finesse (i.e., lift-to-drag ratio) of ZRay during one dive in the Range Validation Test.

The initial nose-down maneuver by ZRay when submerging in order to acquire speed and purge air results in the steep dip in the curve in Fig. 4, between tick marks 200 and 300. After that, the glider establishes steady-state descending flight with an L/D of about 20/1. This value equates to a glide slope less than 3 deg from the horizontal. At the bottom of the dive, the glider must change buoyancy from negative to positive and switch from creating upward lift to downward lift. As a result, the lift-to-drag ratio is zero as the glider coasts thru the apex, around tick mark 600. Once establishing steady-state flight on ascent, the L/D value again reaches 20/1, until coming to the surface where the values return to zero. During this flight, the trailing edge flaps were used only as ailerons to control roll, so that these high L/D ratios were achieved only by creating a high angle of attack.

The sustained L/D ratios of 20/1 illustrated in Fig. 4 are five times or more greater than those of other existing gliders, and were achieved without using the trailing edge flaps to change camber. The L/D ratio is a direct measure of the efficiency of propulsion power consumption in transiting horizontally in the ocean. These sustained L/D values match approximately those calculated using computational fluid dynamical modeling methods. Using the trailing edge flaps to change camber is estimated to nearly double the achievable L/D values.

Because the glide slope is so shallow, the vertical component of velocity used in deriving the curve in Fig. 4 is very small, resulting in a very noisy measurement. Therefore, a significant amount of averaging was used to obtain Fig. 4. An alternative way to measure the "finesse" of the glider is to use the last GPS position fix before submerging at the start of a dive and the first GPS fix upon surfacing at the end of a dive to calculate horizontal distance traveled. This distance along with the measured depth of the dive provides an effective lift-to-drag ratio over ground. This approach requires the glider to fly in approximately a straight line. Fig. 5 shows the results of our first attempt in the Range Validation Test for ZRay to fly itself in a straight line along a constant heading.

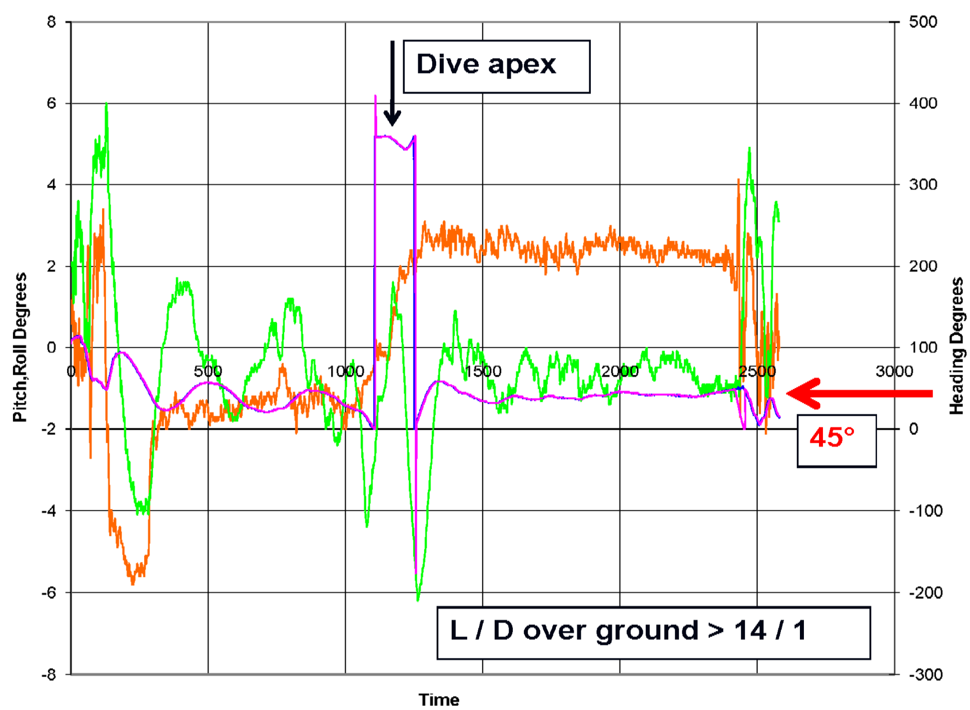

Figure 5. Results from closed-loop heading control during one dive in the Range Validation Test.

The desired heading was 45 deg from magnetic north, as highlighted by the red arrow in Fig. 5. The actual heading of the glider, plotted in purple, was very close to the desired heading. The damped oscillations in heading during the descending part of the dive indicate that the proportional term in the feedback control loop was set a bit too high, leading to some overshoot. As a result of flying at approximately constant heading, the effective L/D over ground for this dive was greater than 14/1, a very encouraging result. Again, the trailing edge flaps acted only as ailerons and were not used to change camber.

During the flight, the roll (green curve) varied by a few degrees about wings level, and the pitch (orange curve) was very stable about 1.5 deg nose down on descent and 2.5 deg nose up on ascent. Throughout descent and ascent, the pitch mass remained fixed – it only was moved at the dive apex. Clearly, active movement of the pitch mass was not required in order to maintain controlled flight, as was the case with XRay. These results demonstrate the significant inherent stability of ZRay in flight.

Both the fluid-based, internal, roll control system (RCS) and the trailing-edge flaps can used to control the glider's roll. Results from the Range Validation Test show that, whereas noise from the operation of the RCS completely dominates the recordings of the leading edge hydrophone array, noise created by operating the flaps to control roll cannot be detected in the single hydrophone spectrograms. In addition, the trailing edge flaps consume less energy than the fluid-based RCS. Therefore, the glider's roll should be controlled by the trailing-edge flaps except when the glider is moving too slowly through the water such as at neutral buoyancy or in creeping flight.

An automated real-time detection and localization algorithm string for use with the leading-edge hydrophone array was installed on a single board computer and integrated into ZRay's payload sphere for the Range Validation Test. This algorithm string is designed to detect and localize calling humpback whales, a species of marine mammals that has not been widely studied in southern California waters. Unfortunately, no low frequency marine mammal calls appear to have been recorded by the ZRay glider's passive acoustic systems during the Range Validation Test. However, the acoustic noise measurements by the leading edge hydrophone array have been extremely helpful in testing and modifying the real-time DCL algorithm string. A few false alarms were recorded by the real-time algorithm during the test, at a rate of about 1 false alarm every 6 hours.

Using the real-time detection/localization algorithm results from the Range Validation Test, a near-optimal algorithm for detecting transient signals was developed. Through numerous Monte Carlo simulations, it was determined that this modified power-law detector performs best when the frequency-bin values are raised to the 6^{th} power, three times greater than that of an energy-based detector, in the case of narrow-band transient signals. Representative results presented as detection error trade-off curves of the detection performance of this generalized power-law processor are given in Fig. 6. The generalized power-law processor with an exponent of 6, modified to detect humpback whale calls in the presence of shipping and wind-generated noise, significantly outperforms energy-based detectors.

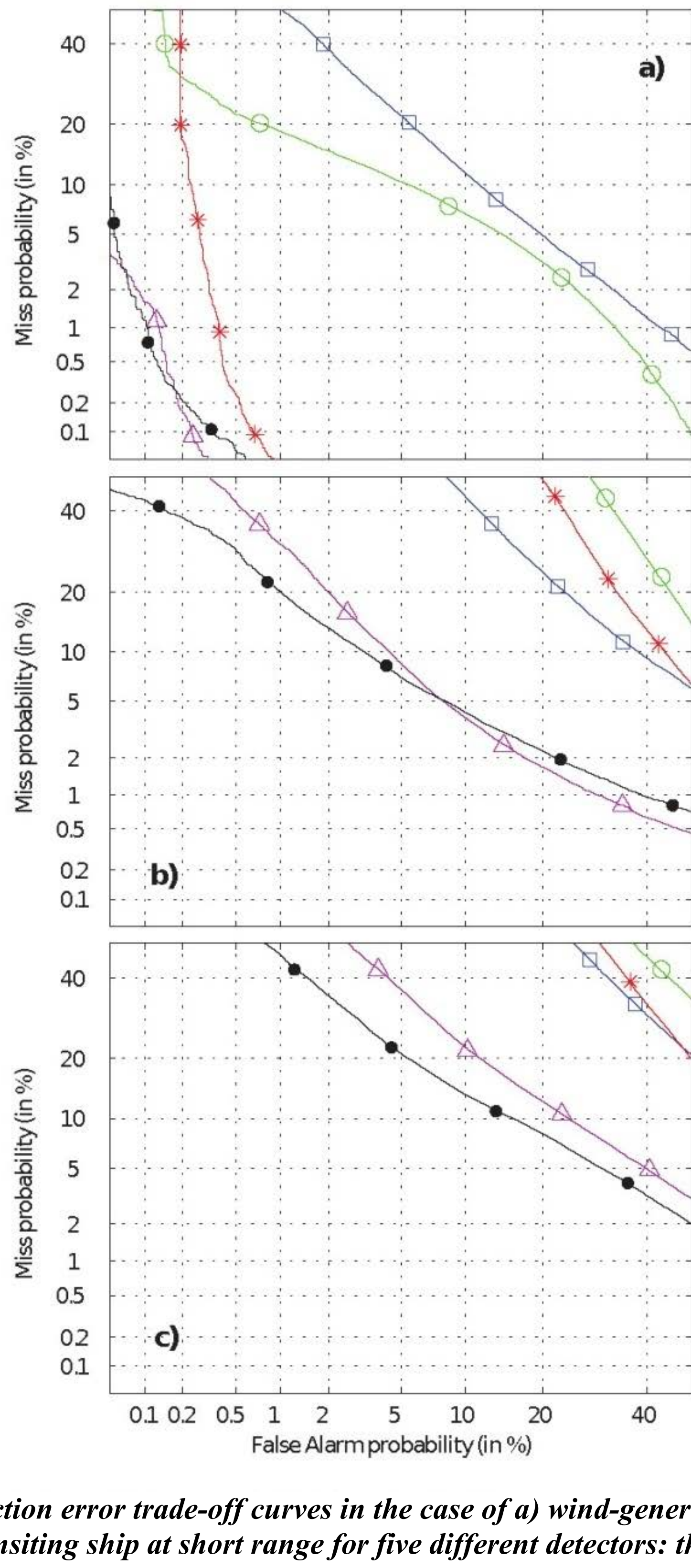

Figure 6. Detection error trade-off curves in the case of a) wind-generated noise, b) distant shipping, and c) transiting ship at short range for five different detectors: the generalized power-law detector (black closed circles), Nuttall's original power-law detector (purple open triangles), the entropy detector (red asterisks), and two versions of an energy-based detector (green open circles and blue open squares).

The software required to permit decisions made by the onboard algorithm string to modify the flight characteristics of the flying wing glider (to enable "whale track-and-trail") presently is ready to be installed and tested during next year's sea tests. This effort is part of the Accelerated Marine Mammal Monitoring Technologies program and forms the basis of the Ph.D. research by Tyler Helble, a Scripps graduate student in the Applied Ocean Science curricular group and Department of Defense SMART fellowship recipient. Tyler took, and successfully passed, his Ph.D. qualifying exam in March, 2011.

IMPACT/APPLICATIONS

Existing underwater gliders (Seaglider, Spray, and Slocum) are highly successful underwater platforms for collecting vertical profiles of water column properties to provide near real-time environmental characterization. In contrast, prop-driven AUVs are designed for level flight, a highly desirable feature for imaging the ocean bottom as required for the mine countermeasure problem. The type of mission suited for the Liberdade class of underwater glider is distinctly different from that of these other two classes of autonomous underwater vehicles. In particular, the flying wing gliders ("Stingray", "XRay", and "ZRay") have demonstrated the capability to minimize energy consumed in horizontal transport while at the same time carry wide-band, multi-channel, high-data-rate payloads and have sufficient physical size to provide large array aperture at low and mid frequencies. The Liberdade class of flying wing underwater glider is well suited for a wide range of Navy missions as well as for long range, energy-efficient sensing of the ocean for basic science and civilian resource monitoring purposes.

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